# THE EMERGENCE OF LAND-SURFACE MODELING IN MODERN-ERA NUMERICAL WEATHER PREDICTION: THE NCEP EXPERIENCE AND COLLABORATIONS

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## 1. INTRODUCTION

In order to sustain continuing advances in numerical weather prediction skill, modern era numerical weather prediction (NWP) and seasonal climate prediction have found it necessary to embrace comprehensive physical treatments of all three earth-system entities of atmosphere, ocean and land. The ocean component includes sea-ice and the land component includes snowpack and vegetation. This paper reviews the emergence of land-surface modeling as an essential component of numerical weather prediction (NWP) and seasonal climate prediction at NCEP, including that of companion data assimilation systems, which span NCEP global and regional reanalysis.

The emergence of land-surface modeling in NWP has benefited greatly from a rich multi-disciplinary legacy that has included satellite remote sensing, hydrology, agronomy, agricultural meteorology, forest meteorology, and air-pollution meteorology. Additionally, since the mid-1980's, advances in land-surface modeling in weather and climate prediction models have been spurred by the growth of research surrounding the prospects of anthropogenic global warming.

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## 2. THE 1960'S, 1970'S & EARLY 1980'S

In NCEP NWP models of the 1960's, 1970's and early 1980's, land surface physics were virtually non-existent, except for simple surface-drag effects on near-surface winds. NCEP's first operational multi-layer model that utilized more than three vertical layers was the N. Hemisphere 6-layer "primitive equation" model (6L-PE) of Shuman and Hovermale (1968), which became formally operational at NCEP on 06 June 1966 on a 381-km hemispheric grid with grid dimensions of 53 x 57. This was the first operational model at NCEP to replace the conservation of vorticity as the central governing equation with the hydrostatic hydrodynamic and thermodynamic equations (undifferentiated and thus referred to as the "primitive equations"). In later years, after the advent of the regional LFM model described below, the 6L-PE was upgraded to the seven layers (7L-PE) and 190-km spatial resolution of the LFM model

The lowest layer of both the 6L-PE and 7L-PE was a crude, constant-depth planetary boundary layer (PBL) of 50-mb thickness. The only land-surface effects in the PE model were twofold: 1) a simple bulk aerodynamic drag term in the predictive equation for the wind components in the model's PBL (using a fixed field for the drag coefficient, which varied spatially as a function of terrain height) and 2) a constant cooling rate applied in the model's PBL layer when a strong winter-night inversion was anticipated -- specifically, when snow cover and sea-ice existed under clear skies at night. The boundaries of snow and ice cover were determined from satellite data provided by the National Environmental Satellite Center, an ancestor of today's National Environmental Satellite, Data, and Information Service (NESDIS). This use of satellite-based snow cover is thought to be the first use of a satellite-derived land-surface product in operational NWP.

The 6L-PE or 7L-PE model had no shortwave or longwave radiative fluxes and hence no diurnal heating. Additionally, the condensation of water vapor to yield precipitation was included very simply via a single governing equation for the total column precipitable water. Furthermore, over land and sea ice, this model had no surface evaporation and no surface sensible heat fluxes, and hence no diurnal cycle such as daily growth and decay of the PBL. Even over ocean, surface evaporation was ignored, though a simple surface sensible heat flux was employed at the bottom of the PBL layer (albeit with no vertical diffusion from the PBL to model layers above). This surface sensible heat flux was based on a bulk aerodynamic law that utilized a fixed surface exchange coefficient applied to the temperature difference between the SST and the model's lowest layer potential temperature. SST was taken from daily analyses performed by the Fleet Numerical Weather Facility.

The Limited Fine Mesh model (LFM) of the 1970's and 1980's was NCEP's first mainstream regional NWP model (Gerrity, 1977; Newell and Deaven, 1980). It executed on seven layers and 190-km resolution the LFM added multi-layer water vapor and precipitation processes, it treated the land-surface almost as simply as the 6L-PE model, though it employed an improved surface friction. Over the ocean, in addition to including surface sensible heat fluxes like the 6L-PE, the LFM added physics for surface latent heat fluxes. However, also like the 6L-PE, the LFM omitted shortwave and longwave radiation, diurnal heating, and surface sensible and latent heat fluxes over land and sea ice.

The global spectral model was implemented at NCEP in the early 1980's (Sela, 1980). During this early 1980's timeframe, the spectral model's treatment of the earth's surface was closely analogous to that of the LFM: namely 1) surface drag was applied to the winds at the model lowest layer, but no vertical turbulent fluxes above this lowest layer were included, 2) surface sensible and latent heat fluxes were included over the ocean, but not over land or sea ice, and 3) shortwave and longwave radiation and diurnal heating were ignored.

## 3. THE LATE 1980'S AND EARLY 1990'S

The addition of serious treatments of the land surface in NCEP models emerged in operations in the mid 1980's. The first instance was in the Nested Grid Model (NGM) (Phillips, 1979) of the NCEP Regional Analysis and Forecast System (RAFS) (Hoke et al., 1989), which was implemented in NCEP operations in March of 1985 at a horizontal resolution of 90-km (inner nest). This initial NGM/RAFS implementation was followed by an NGM/RAFS upgrade in 1986 to a full suite of physical parameterizations (Tuccillo and Phillips, 1986; see also Section 4d of Hoke at al., 1989).

This new suite of parameterized physics included a diurnal cycle of shortwave and longwave radiation interacting with diagnostic cloud cover, stability-dependent PBL mixing, and a land surface energy budget with sensible, latent, and ground heat fluxes modeled via a single-layer, surface-slab model for predicting land-surface skin temperature

(LST), by means similar to the slab-model treatment of Deardorff (1978). The NGM surface-slab model applies an externally supplied snow cover analysis and a crude fixed-field of land-surface wetness (Mitchell, 1994). The latter surface wetness field varied spatially across the model domain, but was invariant in time. Specifically, during the 48-hour NGM forecast, the NGM land-surface wetness and snow cover fraction remained unchanged from their initial conditions, as the effects of the model's precipitation forecast on these fields was ignored, as were the physics of snowmelt and snow sublimation.

The nearly simultaneous upgrade of the NCEP global spectral model in 1986 to a similarly full suite of parameterized physics packages for the diurnal cycle of shortwave and longwave radiation, interactive diagnostic cloud cover, stability-dependent PBL mixing, and a land surface energy budget with sensible, latent, and ground heat fluxes is presented by Kanamitsu (1989) and Kalnay et al. (1990), with early 1990's upgrades to the land surface presented by Pan (1990). Both before and after the latter upgrades, the global spectral model specified its initial soil moisture states from a climatology.

The present successor to the NGM as NCEP's mainline regional forecast model is the Eta model, whose physics package in its initial implementation in the early 1990's is presented by Janjic (1990). In the early 1990's, the Eta model applied a land-surface package much like that of the NGM, including a slab-model for predicting LST. However, this early operational Eta model at NCEP introduced two extensions beyond the NGM. First, the surface wetness field, though still initialized via the aforementioned fixed field (Mitchell, 1994) was allowed to subsequently vary during the model forecast execution in response to model precipitation and surface evaporation, by means of applying the simple bucket model of Manabe (1969). Second, the snow cover fraction was also allowed to vary during the model forecast in response to either model predicted snowmelt or model predicted snowfall.

In both the NGM and early Eta model, the actual surface evaporation was calculated as the product of the fixed field of surface wetness fraction times the potential evaporation (PE). The PE was calculated from a simple bulk aerodynamic formula that applied the difference between the model's lowest layer mixing ratio, Qair, and the saturation mixing ratio, Qsat, given by the model's predicted value of LST. As shown by Pan (1990), this simple bulk aerodynamic method for computing PE overestimates PE substantially, as this calculation is not constrained by surface energy balance. Stated alternatively, the Qsat is overestimated as it is evaluated from the currently predicted LST, rather than the cooler LST that would be realized under conditions of a surface wetness fraction of 1.0 (i.e. under conditions of evaporation occurring at the potential rate). This overestimation of PE by the bulk aerodynamic formulas in the NGM and early Eta model explains why such low values of the surface wetness fraction, such as those depicted in Figure 1, were necessary in the NGM and early Eta model.

The initial snow cover for the global spectral model and regional NGM and Eta models in the 1980's and early 1990's was the then weekly NESDIS 190-km N. Hemisphere snow cover analysis. The weekly update frequency was woefully inadequate for the increasing advancements of the land surface physics in the NCEP models. Frequent near-surface temperature forecast busts during winter in the NCEP models in the late 1980's and early 1990's were traced to the insufficient temporal frequency of the NESDIS snow cover update. Hence around 1992, NCEP requested and soon began receiving in realtime the daily, global, 47-km snow depth analysis (Hall, 1986) of the U.S. Air Force through the NOAA-DOD Shared Processing Network (SPN). Within the next year, the global spectral model, and NGM and Eta regional models were using the daily Air Force snow depth analysis as the source of the models initial snow cover.

**4.0 THE MID 1990'S TO PRESENT**

A key feature of the land-surface treatment in the NCEP global spectral model and the regional NGM and Eta models in the early 1990's period of the previous section is that they were all using a form of the bucket model for their land surface hydrology and either a fixed field for the initial bucket model state (i.e. the cited surface wetness fraction in times the bucket model capacity in the case of the NGM and Eta models) or a monthly soil moisture climatology (in the global model.) The mid 1990's to present represent a period of sweeping changes to the land-surface treatment in the NCEP global model and regional Eta model, and their companion data assimilation systems. (The configuration of the NGM model was frozen in the early 1990's.)

As one preview, as discussed further below, by June of 1998 the data assimilation systems of both the global model and the Eta model were continuously cycling the soil moisture states of their land surface components in their companion, coupled land-atmosphere data assimilation systems. Hence by then, neither fixed fields nor climatologies were being used to initialize the land surface states of the global and regional model. The latter holds also in the counterpart global and regional reanalysis systems that grew out of NCEP's operational global and regional data assimilation systems.

With the above preview in mind, we back up to the mid-90's starting point of the cited sweeping changes. The global model and Eta model advancements in land-surface treatment in the mid 1990's embraced a new baseline given by the Oregon State University land surface model (Pan and Mahrt, 1987; Mahrt and Pan, 1984), denoted henceforth as the OSU LSM. The OSU LSM carries two or more soil layers, a single-layer snowpack, and an explicit vegetation canopy with a companion root zone. With its multi-layer soil profile, the OSU LSM avoids the slab-model approach for soil thermodynamics in favor of the multi-layer thermal diffusion equation for predicting soil temperature.

By January 1995, the NCEP global model had operationally implemented the OSU LSM, with a soil column configuration comprised of two soil layers of 10 and 190 cm thickness. Moreover and just as significantly, by this time the NCEP global data assimilation system (GDAS) based on this global model (and its OSU LSM) applied continuous cycling of its soil moisture states, which thus responded to the surface forcing of the parent atmospheric model during the assimilation phase. Within this continuous cycling of the land states, a very small coefficient (0.05) is used to nudge the soil moisture fields to climatology. This OSU LSM configuration and continuous cycling of the soil moisture states with weak nudging was applied during the NCEP/NCAR Global Reanalysis 1 (Kalnay et al, 1996). Kanamitsu et al. (2002) describe the different approach to soil moisture nudging used in the NCEP/DOE Global Reanalysis 2.

By January 1996, the NCEP Eta model had implemented (Chen et al., 1997) an extended version of the OSU LSM. This version included an extension of the canopy resistance treatment to that of Jarvis (1976), following extensive offline testing of this extended OSU

LSM against three other land surface schemes (Chen et al., 1996). This marked the beginning of a comprehensive and aggressive sequence of upgrades of the OSU LSM in the operational Eta model between January 1996 and February 2002, around the time that the configuration of the Eta model, its companion Eta-based Data Assimilation System (EDAS), and its Noah LSM were frozen for use in the recently completed NCEP 25-year N. American Regional Reanalysis (NARR) (Mesinger et al., 2004; Mitchell et al., 2004). The dates of implementation and nature of these upgrades, as well as examples of their recent impacts in the Eta model are presented in the recent paper by Ek et al. (2003).

The majority of these upgrades took place under the multi-institution collaboration spawned by the Global Energy and Water Cycle Experiment (GEWEX) Continental International Project (GCIP) of the NOAA Office of Global Programs (OGP) (Mitchell, 1994; Lawford, 1999), and its successor, the GEWEX Americas Prediction Project (GAPP). The institutions collaborating with the NCEP land-surface modeling initiatives under GCIP and GAPP include the Office of Hydrological Development (OHD) of the National Weather Service (NWS), the Land Science Team of the NESDIS Office of Research (ORA), the NASA Hydrological Sciences Branch (HSB) of the Goddard Space Flight Center (GSFC), the Air Force Weather Agency (AFWA) and the Air Force Research Lab (AFRL), and a half dozen universities including the University of Maryland, Oregon State University, Rutgers University, Princeton University, the University of Washington, the University of Arizona, and the University of Oklahoma.

In recognition of the comprehensive nature and multi-institution involvement in the upgrades of the OSU LSM at NCEP over the past ten years, NCEP has given the resulting LSM the new name of the "Noah LSM" (Ek et al., 2003). Much of the testing and demonstration of the Noah LSM advances occurred in offline testing and evaluation in the several land modeling foci of GEWEX. These included the Project for Inter-comparison of Land Surface Process Schemes (PILPS) (Henderson-Sellers, 1995; Wood et al., 1998; Schlosser et al., 2000) and the Global Soil Wetness Project (GSWP), Phase I (Dirmeyer et al., 1999), and its presently executing Phase II.

Additionally, the land modeling team at NCEP and its key GCIP and GAPP collaborators has spearheaded the uncoupled North American Land Data Assimilation System (NLDAS) demonstration (Mitchell et al., 2004), which includes streamflow routing for streamflow simulation (Lohmann et al., 2004). The NLDAS has proven to be an excellent test-bed for the performance of the Noah LSM and other LSMs executing in parallel with the Noah LSM. Furthermore, the Noah LSM has been tested extensively in the global extension of the NLDAS, known as the Global Land Data Assimilation System (GLDAS), spearheaded by NASA (Rodell et al., 2004) in a joint grant with NCEP.

Concurrently, under sponsorship of the GCIP and GAPP programs, NESDIS began developing a new higher resolution daily snow cover analysis. This effort culminated in January 1997 with NESDIS implementing the daily, N. Hemisphere 24-km Interactive Multisensor Snow and Sea Ice analysis, known as IMS (Ramsay, 1998). Within a year of that milestone, the NCEP spectral model and NGM and Eta regional models were using the IMS as the operational source of their initial snow cover. In February of this year (2004), NESDIS substantially upgraded the spatial resolution of its N. Hemisphere IMS snow and ice cover product to 4-km. Current and past images of IMS snow cover can be viewed at http://www.ssd.noaa.go/PS/SNOW/index.html.

Simultaneously, NESDIS developed a new, global, 5-year climatology of AVHRR-derived NDVI-based, monthly, 0.144-degree database of green vegetation fraction, or GVF (Gutman and Ignatov, 1998). The LSM component of the NCEP global model and Eta model now use the latter database to operationally and globally specify the annual cycle of the vegetation phenology . Moreover, in February of this year (2004), NESDIS has operationally implemented a realtime weekly update of the global GVF product on the same 0.144-degree global grid (about 14-km resolution). Impact testing of this new weekly realtime global GVF product is now underway in NCEP models.

Finally, the participation of the NCEP land modeling initiative in the GCIP and GAPP programs of NOAA OGP has spawned a wealth of external validations of the performance of the Noah LSM in the NCEP Eta model. Betts et al. (1997) used the special observations of the FIFE field experiment to demonstrate the positive impact in the Eta model of implementing the Noah LSM in place of the legacy bucket model, including a demonstration of the positive impact of the implementation of the cited NESDIS GVF product of Gutman and Ignatov (1998). Berbery et al. (1999) and Berbery et al. (2003) have assessed the Eta/Noah surface energy balance and surface water balance against field observations and other land surface models. Marshall et al. (2003) evaluated the Noah/LSM against the observations of the OU Mesonet, including soil moisture and soil temperature measurements, and included Eta model impact studies that demonstrated the positive impact of the various upgrades later incorporated operationally into the Noah LSM, as described by Ek et al. (2003).

## 5.0 A LAND SURFACE EXAMPLE FROM THE NCEP REGIONAL REANALYSIS

After several years of development sponsored by the Office of Global Programs (OGP) of the National Oceanic and Atmospheric Administration (NOAA) through its GEWEX Americas Prediction Project (GAPP), the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) recently completed 25-years of the NARR for October 1978 through December 2003. The NARR is a long-term, consistent, data assimilation-based, climate data suite for the North American domain, executed at high spatial and temporal resolution (32-km, 45-layer, 3-hourly). In addition, EMC has developed a realtime daily NARR update, known as the Regional Climate Data Assimilation System (R-CDAS). By this summer, R-CDAS will be executed daily by NCEP's Climate Prediction Center (CPC) as a climate-monitoring tool, thus extending the NARR to future years. Together, the retrospective and realtime NARR will span the enhanced observing periods (July 2001 to December 2004) of the Coordinated Enhanced Observing Period (CEOP).

The NARR is based on NCEP's mesoscale Eta forecast model and its Eta Data Assimilation System (EDAS), as configured in NCEP operations in April 2003, when the NARR system was frozen. The NARR employs continuous 3-hour cycling in which a 3-D variational objective analysis updates the background fields of the Eta model. The system was developed as a major improvement in both resolution and accuracy upon the earlier NCEP/NCAR Global Reanalysis 1 (GR1, Kalnay et al., 1996; Kistler et al., 2000) and the NCEP/Department of Energy Global Reanalysis 2 (GR2, Kanamitsu et al., 2002).

In section highlights two key advancements in the NARR over the GRs, namely, the assimilation of observed precipitation fields and the decade of improvements (cited in Section 4) to the Noah LSM, which is the land component of NARR. The most recent Noah LSM improvements and impacts in both uncoupled and Eta model coupled settings are described in several papers in the recent GCIP special issue of the *Journal of Geophysical Research Atmospheres* (Mitchell et al., 2004; Ek et al., 2003; Berbery et al., 2003). Additionally, the NARR improves over the GRs through increased resolution, other new sources of observations (e.g., direct assimilation of satellite radiances), and improved physics (e.g., inclusion of explicit cloud microphysics).

The NARR is summarized in three papers available at the NARR web site: (http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/index.html). They provide 1) a NARR overview (Mesinger et al., 2004), 2) description of NARR input observations and data (Shafran et al., 2004), and 3) summary of the content of and access routes to NARR output (Ebisuzaki et al., 2004). The NARR web site also provides updates on the status of access to the NARR database. The database includes 3-hourly analysis/assimilation fields and fields from companion 72-hour forecasts (initialized every 2.5 days), plus hourly time series at 1300+ sites. NCEP and NOAA's Climate Data Center (NCDC) are populating GrADS DODS (GDS) public servers to allow 1) cost-free distribution of NARR output by ftp (including user-defined sub-setting utilities), 2) interactive user-initiated calculations and plots, and 3) clients such as GrADS running on external servers to access NARR data. Other institutions are arranging to distribute different subsets of the NARR.

As one key subset, NCEP/EMC has derived a "land surface" subset, consisting of land-surface forcing fields (e.g. precipitation, temperature, wind, surface radiation), land-surface states (e.g. soil moisture, snowpack) and land-surface water/energy fluxes. In addition, NCEP/CPC has produced a second key subset that includes 24-year means (1979-2002) of many NARR fields, including monthly means and monthly-mean diurnal cycles for a large number of variables along with, for selected variables, daily means (for each of 365 days) and 3-hourly means (for the mean annual cycle of 365 x 8 times).

In recent years, the poor GR precipitation patterns (from systems that do not include atmospheric precipitation assimilation) have substantially reduced the reliability of GR-derived water and energy budgets, particularly land-surface water budgets. However, it was anticipated that the assimilation of precipitation could reduce the uncertainties and errors in the reanalysis fields. The U.S. hydrological community, which advocated a NARR project from its inception, found particular appeal in the precipitation assimilation and upgraded land-surface components of the NARR.

We briefly summarize here the precipitation assimilation methodology in NARR. All the precipitation analyses ingested in NARR are ultimately disaggregated into hourly analyses on the NARR's background Eta model grid. Over the Continental US (CONUS), Mexico, and Canada, the precipitation disaggregation begins with a daily precipitation analysis (of 24-hour totals) derived solely from gauge observations (see Shafran et al., 2004, and previous newsletter article by Higgins et al.). Over the oceans and the remaining land portions of the NARR domain, satellite-dominated precipitation analyses from CPC are used, though only south of 42.5$^{o}$ N, and their sources and temporal/spatial resolution are different for the retrospective (1979-2002) and realtime NARR (2003-present). For all ocean and remaining land areas north of 42.5$^o$ N, no precipitation data is assimilated. For brevity, we describe the precipitation analysis and its disaggregation only over the CONUS. See Mesinger et al. (2004) and Shafran et al. (2004) for the details in other regions.

Over the CONUS, roughly 12,000 (7,000) gauge observations of daily precipitation totals are available to the retrospective (realtime) NARR and analyzed to a one-eighth-degree CONUS grid using the least-squares distance-weighting scheme of Schaake (2002, personal communication). The latter scheme also applies the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994) climatology of CONUS precipitation to account for orographic influences on precipitation. For a given grid point, any gauge observation within the influence radius for that point is multiplied by the ratio of the PRISM climatology value at the location of the grid point divided by the PRISM precipitation at the location of the observation. The resulting daily precipitation analysis then is disaggregated to hourly by using hourly temporal weights computed in: 1) the retrospective NARR from a 2.5-degree analysis of the lower-density hourly gauge observations of precipitation (many received after realtime); and 2) the realtime NARR from the hourly 4-km WSR-88D radar-dominated precipitation analyses, known as Stage- II/Stage-III. Lastly, these hourly one-eighth-degree analyses are interpolated to the NARR native grid.

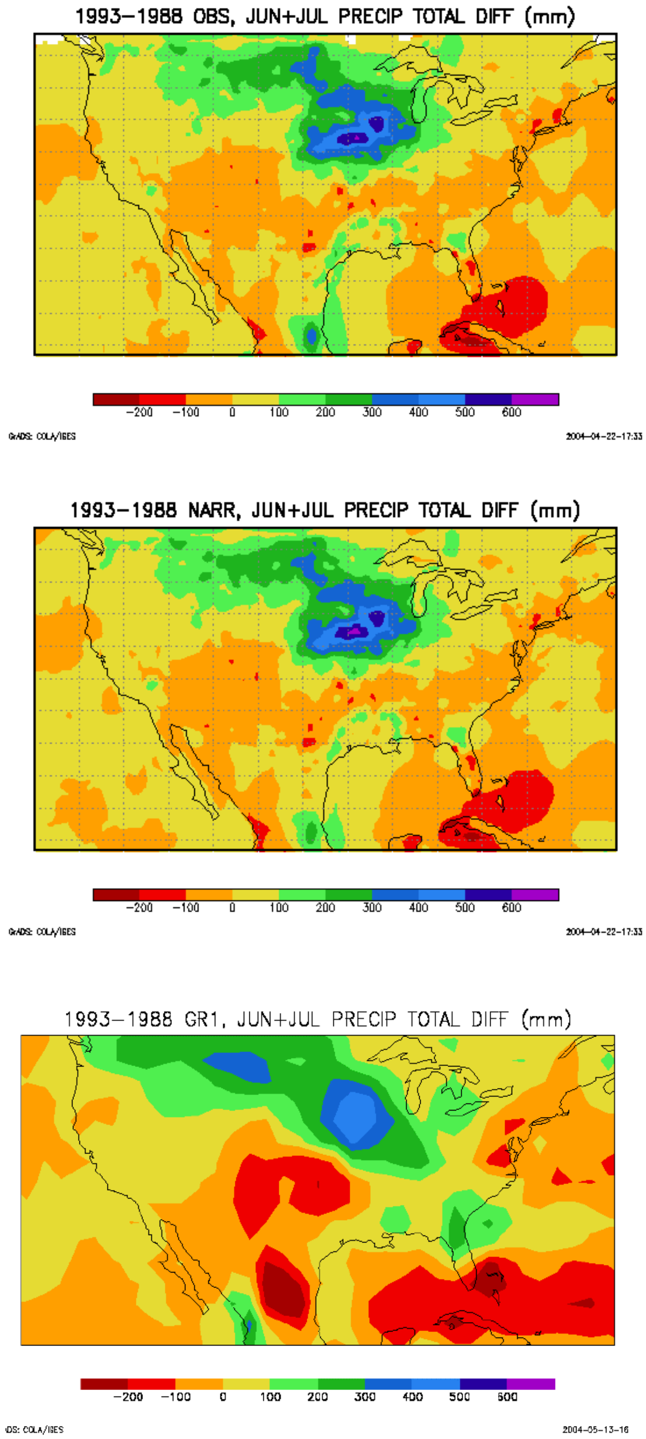
The precipitation assimilation technique in NARR is similar to one developed (Lin et al., 1999) and implemented operationally in EDAS at NCEP. The essential component is a procedure whereby the observed hourly precipitation at any given model grid point is used to adjust the model's vertical profiles of latent heating, water vapor and cloud water during an hourly assimilation interval. To that end, for each time step and each grid point where precipitation observations are available, we compare the model precipitation ($P_{mod}$) against the observations ($P_{obs}$) and make adjustments depending on the following three mutually exclusive precipitation conditions: 1) If $P_{mod} > 0$ but $P_{obs} = 0$, we zero the $P_{mod}$ and take back the corresponding amount of latent heating (cool the temperature) at any model layer where latent heating had been applied and adjust the model's water vapor and cloud condensate mixing ratios to be consistent with zero precipitation; 2) If $P_{mod} > P_{obs} > 0$, we reduce the latent heat release in each precipitating layer by the factor of $P_{obs}/P_{mod}$ and adjust the model's water vapor and cloud condensate mixing ratios to be consistent with reduced precipitation; or 3) If $P_{mod} < P_{obs}$, (including zero model precipitation) we make serial adjustments to, first, conditions in the model's deep convection scheme and, second, to conditions in the grid-scale precipitation physics. Further details on this third and the previous two adjustment categories are online at http://wwwt.emc.ncep.noaa.gov/mmb/ papers/lin/pcpasm/paper.html.

The assimilation of observed precipitation is a critically important addition to the NARR and yields NARR precipitation patterns that are strikingly similar to the ingested precipitation analyses, especially during the warmer seasons. Unlike GR1 and GR2, the NARR effectively reproduces diurnal precipitation signatures over the continental U.S. (CONUS), including a reasonable summertime nocturnal maximum. Over the CONUS, the daily frequency of summer convective precipitation in the NARR is vastly improved over that of GR.

The excellent precipitation patterns produced in the NARR by the assimilation of observed precipitation provide much improved precipitation forcing for the Noah LSM component. The Noah LSM version used in NARR closely follows that described and evaluated in both the coupled Eta/Noah study of Ek et al. (2003) and the uncoupled North American Land Data Assimilation System (NLDAS) study of Mitchell et al. (2004). Briefly, the Noah LSM simulates the soil temperature, soil moisture (including frozen) in four soil layers of 10, 30, 60, and 100 cm thickness. The surface infiltration scheme accounts for subgrid variability in soil moisture and precipitation. The surface evaporation includes direct evaporation from the soil, transpiration from the vegetation canopy, evaporation of canopy-intercepted precipitation, and snow sublimation. The Noah LSM simulates snowpack states of water content, density, fractional coverage and surface albedo via the processes of sublimation, snowfall, and snowmelt (including its partial retention and refreezing) and the snowpack energy fluxes of net radiation, sensible and latent heat flux, subsurface heat flux, and phase-change heat sources/sinks. In the NARR, the snowpack depth is updated once daily from the daily global snow depth analysis (47-km) of the U.S. Air Force, known as SNODEP. This daily update increment is the minimum needed to achieve a NARR snow depth within a factor of two of the Air Force snow depth and becomes an assimilation term in the daily surface water budget.

A warm season example of the difference in NARR land-surface and PBL response between a summer drought episode (1988) and a summer flood episode (1993) over CONUS graphically summarizes these results. In Figure 1, the three precipitation plots show the 1993-minus-1988 difference in June-plus-July total precipitation (mm) from (top) the observed precipitation analyses assimilated in NARR, (middle) the precipitation fields for the same period produced by NARR, and (bottom) the precipitation fields for the same period produced by GR1. The close agreement between observations and NARR is clear. In contrast, the GR1's positive precipitation anomaly in the central CONUS is spatially too broad and bland, and it extends too far to the northwest and southeast. Meanwhile, the GR1 negative anomaly is too dry in the southern Great Plains and northern Mexico.

The NARR precipitation anomaly cited above is well manifested in NARR mid-July soil moisture states, depicted in Figure 2 for 1988 (top) and 1993 (bottom). Over the central CONUS, the much wetter soil (and more cloud cover, not shown) in NARR in mid-July 1993 (bottom) vs.1988 (top) yields (not shown) much lower mid-day surface sensible heat flux and skin temperature. In turn, this lower sensible heat flux in 1993 vs. 1988 produces a notably lower planetary boundary-layer depth over central CONUS in 1993 (Figure 3, bottom) vs. 1988 (Figure 3, top). The 2-week mean fields of July 16-31 (not shown) corresponding to the four 15 July figures of Figures 2 and 3 show analogous features.



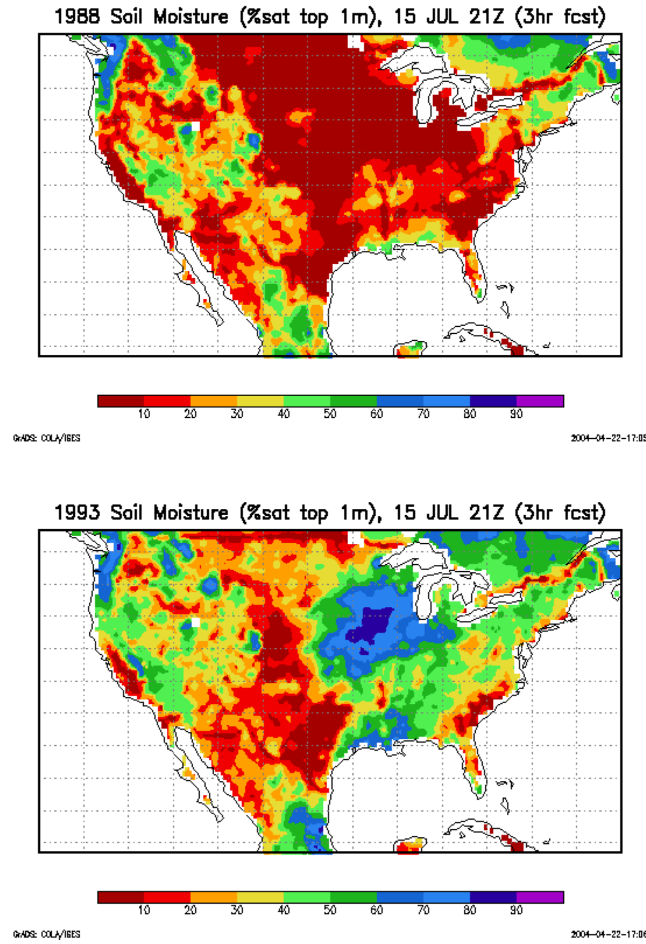




**Figure 2.** Soil moisture (as percent of saturation) of N. American Regional Reanalysis for top 1-meter of soil column valid at 21 UTC for 15 July of 1988 (top) and 1993 (bottom).

**Figure 1.** The 1993-minus-1988 difference in June-plus-July total precipitation (mm), from gauge observations (top), N. American Regional Reanalysis (middle), and Global Reanalysis 1 (bottom).

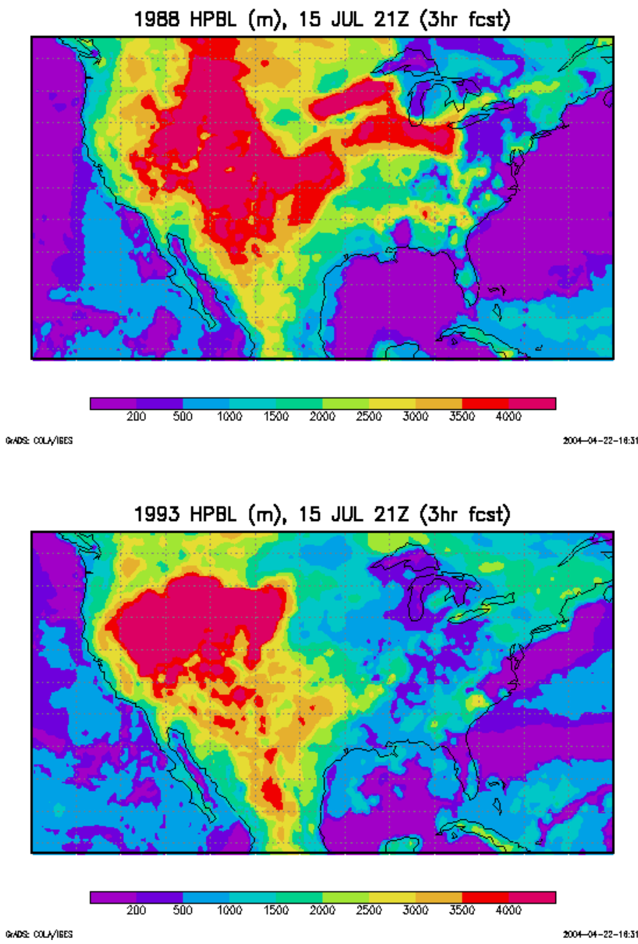



**Figure 3**. Planetary boundary layer depth (m) of the N. American Regional Reanalysis valid at 21 UTC for 15 July of 1988 (top) and 1993 (bottom).

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